REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE: April 1993

3. REPORT TYPE AND DATES COVERED: professional paper

4. TITLE AND SUBTITLE: POSSIBLE RELATIONSHIP BETWEEN OCEANOGRAPHIC CONDITIONS AND LONG-RANGE DETECTION BY A FALSE KILLER WHALE

5. FUNDING NUMBERS: PR: MMB2; PE: 0602435N; WU: DN688674

6. AUTHOR(S): C. W. Turl, J. A. Thomas

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES):
Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
San Diego, CA 92152-5001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES):
Naval Command, Control and Ocean Surveillance Center (NCCOSC)
RDT&E Division
Block Programs
San Diego, CA 92152-5001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT: Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A false killer whale (*Pseudorca crassidens*) target detection experiment was conducted on the Skyhook II biosonar target range in Kaneohe Bay, Hawaii. The target was a 7.62-cm diameter stainless-steel sphere. The target distance varied from 80 to 120 m. Normally a morning (0800) and afternoon (1300) test session was conducted each day. The maximum target detection threshold at 50% correct detection for all test data was estimated to be 117 m. There was, however, a significant difference in the whale's performance between the morning and afternoon test sessions. At target distance greater than 95 m the whale's average performance was 52% correct detection during the morning and 91% correct detection during the afternoon test session.

We took conductivity and salinity measurements by depth at distances of 0, 50, 100, and 200 m along the range. Sound velocity profiles for each cast were calculated. In the morning, the surface (<1 m) water temperature and salinity were more variable among the casts, resulting in different sound velocity profiles along the range. Although in some cases the differences were small, their cumulative effects along the range seemed to lower the whale's performance. In contrast, during the afternoon sessions, water temperature, conductivity, and the resulting sound velocity profiles for the four casts along the range were more similar from the surface to the bottom which seemed to be related to the whale's higher detection performance.

A number of factors could have contributed to the whale's low morning performance and high afternoon performance, including the animal's motivation, familiarity with the target detection task and variation in noise or reverberation. However, from the oceanographic data that we collected during the course of this experiment and the variation between the morning and afternoon sound velocity profiles we suggest that the afternoon sound propagation characteristics contributed to the higher detection performance.

Published in *Sensory Abilities of Aquatic Mammals*, Plenum Press, pp. 332-341.

14. SUBJECT TERMS: marine biosystems; marine biology; marine animal

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

21a NAME OF RESPONSIBLE INDIVIDUAL	[illegible] TELEPHONE [illegible]	[illegible]
C. W. Turl	(619) 553-5451	Code 512

Possible Relationship Between Oceanographic Conditions and Long range Target Detection by a False Killer Whale

by

Charles W. Turl[1] and Jeanette A. Thomas[2]

[1]Naval Ocean System Center, Hawaii Laboratory, Kailua, Oahu, Hawaii

[2]Office of Aquatic Studies, Western Illinois University, Macomb, Illinois

ABSTRACT

A false killer whale (Pseudorca crassidens) target detection experiment was conducted on the Skyhook II biosonar target range in Kaneohe Bay, Hawaii. The target was a 7.62-cm diam. stainless-steel sphere. The target distance varied from 80 to 120 m. Normally a morning (0800) and afternoon (1300) test session was conducted each day. The maximum target detection threshold at 50% correct detection for all test data was estimated to be 117 m. There was, however, a significant difference in whale's performance between the morning and afternoon test sessions. At target distance greater than 95 m the whale's average performance was 52% correct detection during the morning and 91% correct detection during the afternoon test session.

We took conductivity and salinity measurements by depth at distances of 0, 50, 100, and 200 m along the range. Sound velocity profiles for each cast were calculated. In the morning, the surface (<1m) water temperature and salinity were more variable among the casts, resulting in different sound velocity profiles along the range. Although in some cases the differences were small, their cumulative effects along the range seemed to lower the whale's performance. In contrast, during the afternoon sessions, water temperature, conductivity, and the resulting sound velocity profiles for the four casts along the range were more similar from the surface to the bottom which seemed to be related to the whale's higher detection performance.

A number of factors could have contributed to the whale's low morning performance and high afternoon performance, including the

animal's motivation, familiarity with the target detection task and variation in noise or reverberation. However, from the oceanographic data that we collected during the course of this experiment and the variation between the morning and afternoon sound velocity profiles we suggest that the afternoon sound propagation characteristics contributed to the higher detection performance.

INTRODUCTION

The velocity of sound is an oceanographic variable that determines many peculiarities of the sound transmission in the ocean (Urick, 1967). Factors affecting the velocity of sound include temperature, salinity and depth as well as season, geographical location and with time at a fixed location. These, coupled with noise and reverberation, combine to affect the performance of any sonar. The "afternoon effect" (Urick, 1967) illustrates the relationship between diurnal changes of sound velocity and the effect on sound transmission from a surface-ship sonar.

In shallow coastal waters, sound velocity profiles (the change in the speed of sound over depth) sometimes are irregular and unpredictable (Pritchard, 1967). Rain or freshwater runoff may change salinity and thus, sound velocity gradients may vary over time (Urick, 1967). Water temperature can cause considerable change in the sound velocity profile. In shallow water, surface weather conditions, season of the year, and time of day affect sound velocity profiles (Tucker and Gazey, 1966).

If there is no change in the sound velocity with depth (isovelocity profile), sounds tend to propagate in a direct path. If sound velocity decreases with depth (negative velocity profile) sound waves bend downward and then can reflect off the bottom. When sound velocity increases with depth (positive velocity profile) sound waves refract upward and subsequently can reflect from the surface. We reason that differences in sound velocity profiles caused by temperature and salinity changes may also affect the propagation of echolocation signals from cetaceans. This effect may become especially pronounced in shallow water.

Thomas and Turl (1990) reported the 50% correct detection threshold for a false killer whale (Pseudorca crassidens) detecting a 7.62-cm diameter stainless steel, water-filled sphere 1 m below the surface was 117 m. This threshold distance is comparable to the threshold of 113 m reported for a bottlenose dolphin (Au and Snyder, 1980) and 116 m measured for a beluga (Turl and Penner, unpubl.) on the same test range. The number of correct detection by the false killer whale was quite variable between morning and afternoon sessions. Performance during the morning session sometimes was as low as chance and then increased to 100% during the afternoon session on the same day.

The effects of noise and reverberation on a cetacean's sonar shows that as the noise or reverberation increases the animal's detection performance decreases (Au and Penner, 1981; Au and Turl, 1983; Turl et al., 1987; Turl et al., 1991); however, how oceanographic variables affects a cetacean's sonar performance has not been studied.

We wondered how oceanographic conditions might be changing and affect the transmission characteristics along the range. Using a SEACAT Profiler, we took casts for temperature and salinity by depth before sessions at four distances along the target range. Herein, we retrospectively describe oceanographic conditions during the tests and discuss how sound propagation characteristics along the shallow target range may have contributed to variability in performance by the false killer whale.

I. METHODS

A. Description of Skyhook II Range

Skyhook II is located at Sag Harbor in the south-east basin of Kaneohe Bay, Oahu, Hawaii (Figure 1). This area is relatively estuarine, with limited circulation because of a shallow coral reef border that restricts connection to the open sea (Evans and Simmons, 1977). Flushing of the bay is by tidal action and may be assisted or impeded by winds. During heavy rainfall, runoff can contribute as much as 4.8% of the total bay volume, so that at certain times the inshore coral flats can be flooded with a surface layer of fresh water. Minimum surface water temperature and salinity occur in January and November, respectively. Typically, maximum rainfall is during November (Bathens, 1968). Therefore, our November range detection study was conducted at an oceanographical dynamic time of the year.

The Skyhook II target range consists of two vertical poles mounted on piers spaced approximately 200 m apart. A catenary suspension between the two poles allows targets to be positioned at any distance between the poles and raised and lowered with a monofilament line that extends back to the experimenter's station. The Skyhook II range runs parallel to and is approximately 50 m from the shoreline of Sag Harbor. Two drainage culverts are located at about 50 and 120 m along the range. South Pond is located directly behind the range and discharges brackish water directly into Sag Harbor (Figure 1).

B. Data collection procedures

A trial began when the whale was in front of the experimenter, opposite the hoop station [see Fig.2 in Thomas and Turl (1990)]. A 3 kHz tone was presented that released the whale to swim across the pen and insert its head into the stationing hoop that was at 0 m on the range. An acoustic screen, made of aluminium and neoprene rubber was in front of underwater hoop station to prevent the whale from echolocating the target. The target was either gently lowered into the water or left out, and the acoustic screen was lowered, which cued the animal to begin echolocating. The center of the hoop and target depth were both positioned 1 m below the water surface. The whale ensonified the range for as long as it desired, backed out of the hoop, and responded by touching either a paddle on the right (to indicate target present) or a paddle on the left (to indicate target absent). The whale received fish reinforcement for correct responses.

Data were collected during a morning and an afternoon session five days per week. A session consisted of 50 trials divided into five blocks of 10 trials. Each block was assigned a different target distance. Equal number of target-present and target-absent trials were distributed randomly in a block based on modified Gellerman (1933) tables. Only the correct detection (target present) trials were used to calculate performance.

C. Sound Propagation Measurements

Before the start of 22 sessions, temperature and salinity were measured by depth at four locations along the Skyhook II range (0, 50, 100 and 200 m) using a Sea-Bird SEACAT profiler. For each cast, water temperature (degrees C) and salinity (ppm) as a function of depth were stored in the profiler's memory. These data were downloaded to a Compaq 386 personal computer and sound velocity profiles calculated by SEACAT software. Because water depth varied along the range, we limited comparisons of cast data to depths between 0.4 and 4.0 m.

II. RESULTS

A. Performance

The false killer whale's average correct detection performance (dashed line) between 90 and 120 m is plotted in Fig. 2. Also shown is the whale's average correct detection performance for morning and afternoon data sessions. Morning and afternoon performance at each distance was compared using a student's t-test with pair wise comparisons ($p < .05$). At target distance greater than 95 m, the whale's performance was significantly different between morning and afternoon sessions.

B. Sound Velocity Profiles

The variability of the sound velocity profiles (SVP's) along the test range was quite variable. Figure 3A shows morning SVP's and Figure 3B shows the afternoon SVP's for 7, 15, 22 and 28 November. In the morning, a surface velocity gradient was observed at least at one station along the range; whereas, the afternoon sound velocity profiles for the same days are relatively consistent along the range. Figure 3C compares less extreme SVP's measured on 29 November for morning and afternoon.

The average morning (circle) and afternoon (solid line) sound velocity profiles for all cast data are compared in Figure [illegible] with the standard deviation (morning as error bar, afternoon as shaded area). In the morning, the sound velocity profiles between the surface and 1.[illegible] m varied as much as ±[illegible] meters per second compared to about ±1 meter per second along the range in the afternoon. The area beyond 50 m from the hoop station tended to show the greatest variability in the morning. Cast data indicates that the water column along the range can have an upper and lower layer. The upper layer is probably influenced by rain, runoff, and surface conditions, whereas the lower layer is supplied by Kaneohe Bay and protected from surface conditions and weather.

Figure 5 plots average sea surface temperature and wind speed in Sag Harbor during the month of November (Grovhoug, pers comm). Water column mixing is affected by water temperature, wind speed, and currents. Both surface sea temperature and wind speed begin to increase during the morning and reach a maximum after 1200 hrs which probably contributed to uniform surface temperature and salinity in the afternoon.

C. Sound Velocity Profiles and the Whale's Detection Performance.

We correlated the whale's average performance to differences in sound velocity between the whale and the target (Figure 6). We defined the maximum difference in sound velocity among the four casts at 1 m below the surface (or the depth of the whale and the target) as Delta Axial Sound Velocity. A high negative correlation of R=-0.91 indicated a strong relationship between high performance and low variation in sound velocity at a 1 m depth along the range. A comparison of the maximum difference in

Delta Axial Sound Velocity between 0 and 50 m and between 0 and 100 m produced similarly high negative correlations of $R = 0.89$ and $R = 0.93$, respectively.

Figure 7 shows a significant direct relationship ($p < 0.01$) the whale's average performance and the correlation between the sound velocity profiles from the surface to 4.0 m depth at the animal (0 m) and at 50 m {$F(1,21) = 26.7$, 0} and between the sound velocity profiles at the animal and at 100 m {$F(1,21) = 61.92$, 0}.

Using a simple, flat surface ray tracing model, we plotted (Fig. 8) the transmission of a single direct path sound ray from the animal as it might be influence by the sound velocity profile we measured at 0, 50, and 100 m along the range on the morning of 29 November (Fig. 3C). In the afternoon sound velocity profiles at all three distances would promote relatively direct path transmissions from the whale (dashed lines) to the target and back. In contrast, sound velocity profiles in the morning (solid lines) would result in quite different transmission patterns from the whale to the target and back.

III. DISCUSSION AND CONCLUSIONS

In shallow water, localized, inhomogeneities in sound velocity may exist between a sound source and a receiver. Sounds propagating across adjacent, different sound velocity profiles may results in a complex and unpredictable sound field near the target. These conditions can cause human-made sonars to have ping-to-ping and echo-to-echo variability (Urick, 1967). These shallow water variations may have caused similar problems for the false killer whale during our range detection study.

In this study, the false killer whale's detection performance decreased as the target moved further away, especially between 90 and 120 m. Some variability in an animal's performance is expected and there are behavioral and experimental factors that may affect the performance of any biological sonar. However, in this study we could not explain the difference in performance between morning and afternoon sessions by experimental design, animal learning, or animal motivation. All test procedures were the same for morning and afternoon sessions. Targets at all distances were tested in a near-to-far sequence followed by a random series and the whale's performance was not significantly different for near-to-far versus a random series (Thomas and Turl, 1990).

Kaneohe Bay is dominated by snapping shrimp noise that shows a slight diurnal variation. Albers (1965) reports that snapping shrimp noise levels are 2 to 5 dB higher at night with a slight peak just after sunset and just before sunrise. Because we did not monitor snapping shrimp levels, we do not know if the noise levels changed during our study or if they could have affected the false killer whale's performance. In addition, schooling fish are seasonal in Kaneohe Bay (Henderson, pers comm). The presence of fish schools between the whale and the target could have increased reverberation, but we did not monitor the presence or absence of fish schools during our sessions.

During this study there were several trends that we think were significant: (1) our shallow water tests were conducted during a oceanographical dynamic period of the year, and (2) early afternoon environmental conditions promoted surface water mixing, which may have contributed to more uniform sound propagation along the target range. We do not know whether primarily one or a combination of these factors is responsible for differences in the whale's performance. However, when the sound propagation conditions along the range were more consistent and signals traveled a direct path the whale's detection performance improved.

Changing oceanographic conditions during perceptual tests close distance probably have a limited influence on echolocation abilities of a whale. However, when a cetacean needs to detect a target over a long range in an open-water environment the environmental conditions should be examined. We recommend that oceanographic conditions such as surface wind speed, water temperature profiles, salinity profiles, and tidal patterns should be measured in open-water echolocation studies. In addition, monitoring biological conditions, such as ambient noise and the movements of schooling fish, may provide useful information in interpreting the performance of cetaceans in long-range, open-water echolocation tests.

FIGURES

Figure 1. Map of Sag Harbor in Kaneohe Bay, Oahu, Hawaii, designating Skyhook II , two drainage culverts, and South Pond location.

Figure 2. False killer whale's average performance for target present trials (dashed line) by distance. Average morning (closed triangles) and afternoon (open triangles) from 90 to 120 m.

Figure 3. Morning (A) and afternoon (B) sound velocity profiles for 7, 15, 22 and 28 November, 1988. Data taken from four casts along the range at distances of 0, 50, 100, and 200 m. 3C. Morning and afternoon sound velocity profiles for 29 November, 1988.

Figure 4. Average morning (circles) and afternoon (solid line) sound velocity between 0.4 and 4.0 m for all cast data. The error bars (morning) and shaded area (afternoon) represents 1 standard deviation of the data.

Figure 5. Average daily surface wind speed (km/h) and surface water temperature (degrees C) at Sag Harbor in November. Shading designates session times.

Figure 6. False killer whale's average performance versus the Delta Axial Sound Velocity for morning (solid circles) versus afternoon (open circles).

Figure 7. False killer whale's average performance versus the degree of correlation between the sound velocity profile at the whale and at 50 m (triangles) and between the sound velocity profile at the whale and at 100 m (circles).

Figure 8. Ray diagram of sound velocity profiles at three distances along the range on the transmission of a direct path for

the morning versus afternoon sessions on 29 November, 1984. Note that the sound propagation conditions during the morning produce more variable transmission patterns than conditions during the afternoon.

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